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Improving resistivity survey resolution at sites with limited spatial extent using buried electrode arrays

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ABSTRACT

Electrical resistivity tomography (ERT) surveys are widely used in geological, environmental and engineering studies. However, the effectiveness of surface ERT surveys is limited by decreasing resolution with depth and near the ends of the survey line. Increasing the array length will increase depth of investigation, but may not be possible at urban sites where access is limited. One novel method of addressing these limitations while maintaining lateral coverage is to install an array of deep electrodes. Referred to here as the Multi-Electrode Resistivity Implant Technique (MERIT), self-driving pointed electrodes are implanted at depth below each surface electrode in an array, using direct-push technology. Optimal sequences of readings have been identified with the "Compare R" method of Wilkinson. Numerical, laboratory, and field case studies are applied to examine the effectiveness of the MERIT method, particularly for use in covered karst terrain. In the field case studies, resistivity images are compared against subsurface structure defined from borings, GPR surveys, and knowledge of prior land use. In karst terrain where limestone has a clay overburden, traditional surface resistivity methods suffer from lack of current penetration through the shallow clay layer. In these settings, the MERIT method is found to improve resolution of features between the surface and buried array, as well as increasing depth of penetration and enhancing imaging capabilities at the array ends. The method functions similar to a cross-borehole array between horizontal boreholes, and suffers from limitations common to borehole arrays. Inversion artifacts are common at depths close to the buried array, and because some readings involve high geometric factors, inversions are more susceptible to noise than traditional surface arrays. Results are improved by using errors from reciprocal measurements to weight the data during the inversion.

1. Introduction

Electrical resistivity is a widely used geophysical method for investigating geological and hydrogeological (e.g. Kruse et al., 1998; Daniels et al., 2005; Nenna et al., 2011; Singha et al., 2014; Yeboah-Forson et al., 2014) engineering (Wilkinson et al., 2006a; Danielsen and Dahlin, 2010), mining (Legault et al., 2008) and environmental problems (Slater et al., 2000; Pidlisecky et al., 2006; Meju, 2006; Chambers et al., 2010; Power et al., 2015). The method can be applied to such a wide range of problems because measurements are sensitive to lithology, degree of saturation, and pore water composition (e.g. Lesmes and Friedman, 2005). Reviews of the recent developments in electrical resistivity tomography (ERT) are given by Dahlin (2001), Auken et al. (2006) and more recently by Loke et al. (2013).

During a resistivity survey DC current is driven through the earth between pairs of electrodes installed at the surface or buried at depth. While current flows, electric potential differences are measured between other pairs of electrodes. The measured potential differences are related to the resistivity structure of the ground through which the current flows. There is clearly infinite flexibility in how the electrodes used to drive current and those used to measure potential can be spatially configured. Use of traditional electrode arrangements with simple rules for displaying apparent resistivities as pseudo- sections, such as Wenner (e.g. Loke, 2010) and dipole–dipole arrays (e.g. Telford and Sheriff, 1990), persists even after the development of commercial systems that can automate acquisition of more flexible array geometries.

Current commercial resistivity systems offer automated switching capabilities for driving current and measuring potentials, so users install an array of electrodes, often ~30–100. Then a sequence of readings is taken by addressing pairs of current and potential electrodes within the array. Most surveys conducted today are two-dimensional (2D); a series of electrodes are laid out in a straight line. Typically electrodes

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are evenly spaced along the line. Such conventional 2D surveys are logistically efficient to deploy, but there are well-recognized limitations to conventional 2D surveys, which are discussed further below.

Other arrangements of electrodes have been tested and described, including 3D surveys in which electrodes are arranged in grids on the surface (Loke and Barker, 1996; Tsourlos and Ogilvy, 1999). More labor-intensive methods involve installing electrodes in vertical downhole arrays, for cross-borehole surveys (e.g. Daily and Owen, 1991; Slater et al., 2000; Perri et al., 2012). Pidlisecky et al. (2006) used deep electrodes as current source in resistivity measurements done using a cone penetration testing (CPT) rig. Danielsen and Dahlin (2010) used horizontal boreholes drilled on the working face of a tunnel boring machine (TBM) to gain information about the rock conditions before the next heading. Power et al. (2015) demonstrated improved time-lapse monitoring of contaminant remediation using surface-to-horizontal borehole ERT relative to surface ERT. Simyrdanis et al. (2015) used surface-to-tunnel electrical resistivity tomography to study the subsurface between the ground and a tunnel. Clearly, the current state of the practice in resistivity surveys offers unprecedented flexibility in the spatial positioning of a set of electrodes.

In this paper, we describe and test a new arrangement of electrodes in which a series of electrodes are individually vertically implanted at a uniform depth, to form a buried horizontal array. This arrangement addresses two fundamental limitations of conventional 2D arrays. The optimization of readings within the new array is the focus of a separate paper, Loke et al. (2015) which discusses the advantages of optimized MERIT arrays over manually created MERIT arrays. With 2D surveys, two significant limitations arise that are particularly acute in urban settings. First, 2D surveys resolve resistivities to depths considerably shallower than the total array length. Where practitioners are limited to access on a single plot of land, the array length, and hence the depth of resolution, is constrained by the plot boundaries. This can be a critical shortcoming if the target of interest lies below the plot-limited depth of penetration. The problem is exacerbated when shallow conductive layers further inhibit deep current flow. Second, 2D surveys lose resolution at the ends of the survey line (Loke, 2010). Cross-borehole surveys, with readings made between electrodes in paired boreholes, can overcome the sensitivity limitations at depth. But the cost of drilling boreholes is relatively high, and, because of this installation expense, the number of holes is often limited, and hence lateral coverage is also limited.

Here we use a novel technique to enhance depth of sensitivity, with increased lateral resolution along the surface array length. This is done by implanting half of the electrodes at a depth closer to the subsurface target features, using an efficient direct-push technique (Fig. 1a, b and c). To make installation efficient and robust, deep pointed implant electrodes were designed to facilitate vibration resistance while being driven into the ground with minimal impact (Harro and Kruse, 2013). This array geometry is referred to as the multi - electrode resistivity implant technique, or MERIT. The presence of deep electrodes allows higher signal strength and sensitivity at depth even when the survey length is small. Even in areas where a longer survey would be feasible, a shorter MERIT array can avoid unwanted sensitivities to features off the survey line (e.g. Dahlin, 2001). The installation method is further discussed down below.

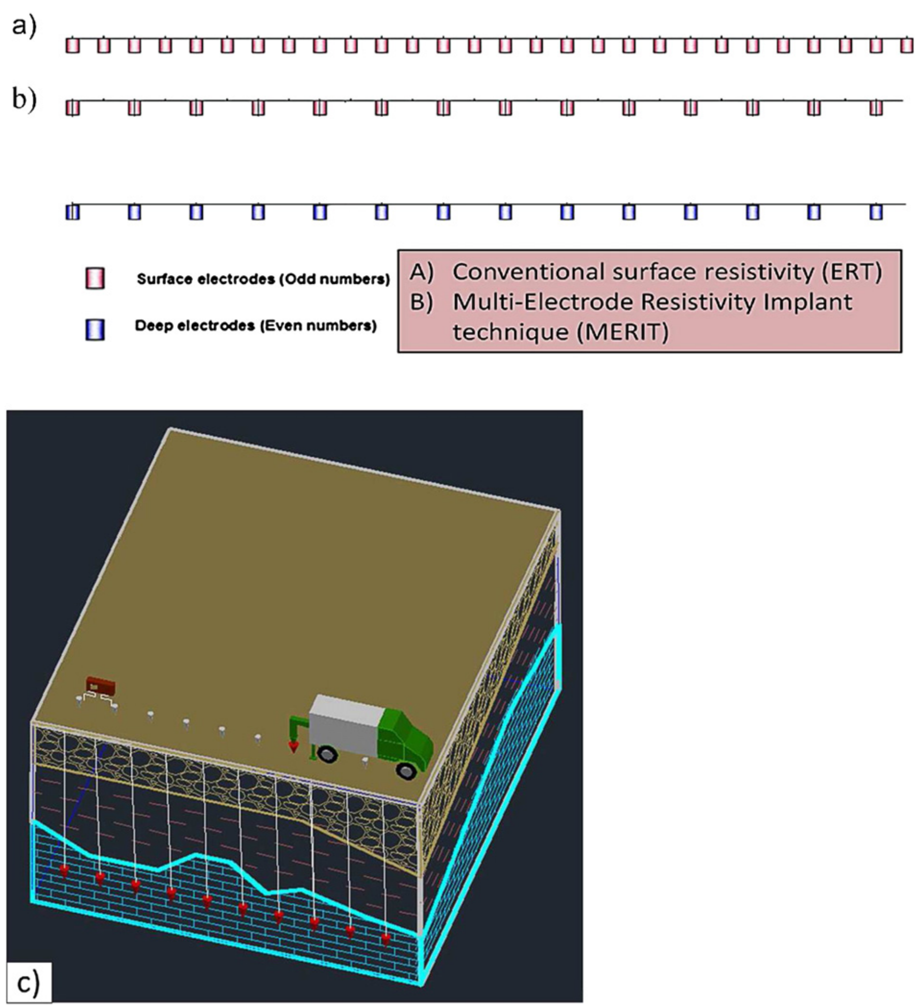

Fig. 1. (a) Field arrangement of a conventional surface array. (b) Field arrangement of MERIT array. c) Schematic diagram showing the installation of MERIT arrays.